

Static Synchronous Series Compensator (SSSC) with Superconducting Magnetic Energy Storage (SMES) for the Enhancement of Transient Stability in Multi-Area System

S. Padma^{#1}, Dr. R. Lakshmi^{*2}

[#]Electrical and Electronics Engineering Department, Anna University,
Sona College of Technology, Salem-5, Tamilnadu, India.

^{*}Electrical and Electronics Engineering Department, Anna University,
St Peter's Engineering College, Chennai, Tamilnadu, India.

¹swanisha@gmail.com

²drllakshmi@yahoo.com

Abstract— Static Synchronous Series Compensator (SSSC) has been designed with Superconducting Magnetic Energy Storage (SMES) system. A closed loop control scheme has been proposed with PI controller and real and reactive powers are taken as references. A 48 pulse voltage source inverter is designed for the SSSC. Control scheme for the chopper circuit of SMES coil is also designed. A three area system is taken as the test system and the operation of SSSC with SMES is analysed for various transient disturbances. Test results under different disturbances and operating conditions show the proposed SSSC with SMES is effective in damping out the power system oscillations.

Keywords— SSSC, SMES, Transient stability, voltage source inverter, closed loop control

I. INTRODUCTION

Today's modern interconnected power system is highly complex in nature and the electrical power consumptions and transactions have rapidly increased. Under these circumstances the keen issue is how to expand the existing transmission equipment to meet the growth of demands in an economical way. Maintaining stability of such an interconnected power system has become a cumbersome task. As a countermeasure against these problems, the Flexible AC Transmission System (FACTS) devices were proposed and the prototypes have been developed. The applications of FACTS devices to improve system damping against both dynamic and transient stability have been reported in the literature [1]-[2].

Simultaneous real and reactive power control has also been proposed in the literature [3]-[5]. In this sense, research in this field has been lately extended with the aim of incorporating power electronic devices into electric power systems - FACTS devices. Presently, these devices are a viable alternative as they allow controlling voltages and currents of appropriate magnitude for electric power systems at an increasingly lower cost [6]. However, a comparable field of knowledge on FACTS/ESS control is quite limited. Therefore, in this work a methodology is proposed to control

the power flow, which uses FACTS controllers with energy storage. The switching power converter-based FACTS controllers can carry this out. Among the different variants of FACTS devices, Static Synchronous Series Compensator (SSSC) is proposed as the most adequate for the present application. The DC inner bus of the SSSC allows incorporating a substantial amount of energy storage in order to enlarge the degrees of freedom of the SSSC device and also to exchange active and reactive power with the utility grid. Based on a previous study of all energy storage technologies currently available, the use of Superconducting Magnetic Energy Storage system (SMES) is proposed for the considered application [7]-[9].

This paper proposes a detailed model of an SSSC with and without SMES, and a PI control algorithm for this combined system to carry out the power flow control of the electric system. This paper also lays the foundations for an increased operational flexibility by integrating energy storage devices with other power converter-based FACTS controllers' structures. The SMES coil is connected to the VSI through a dc-dc chopper. It controls dc current and voltage levels by converting the inverter dc output voltage to the adjustable voltage required across the SMES coil terminal. A two-level three-phase dc-dc chopper used in the simulation has been modeled and controlled according to [15], [16].

Details on operation, analysis, control strategy and simulation results for SSSC with and without SMES are presented in the subsequent sections.

II. OPERATION OF SSSC WITH SMES

SSSC is a voltage sourced converter based series compensator. The compensation works by increasing the voltage across the impedance of the given physical line, which in turn increases the corresponding line current and the transmitted power. For normal capacitive compensation, the output voltage lags the line current by 90°. With voltage source inverters the output voltage can be reversed by simple control action to make it lead or lag the line current by 90°.

The single line diagram of the multi-machine system used for the simulation study is shown in Fig. 1.

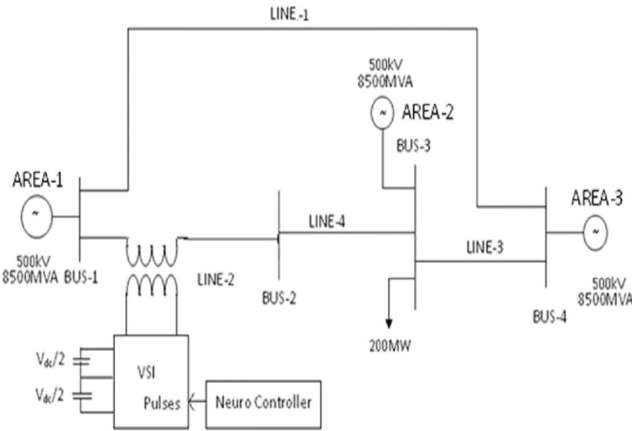


Fig. 1. Single line diagram of the test system with SSSC.

If V_s and V_r are the sending end and receiving end voltages, then the real and reactive power (P & Q) flow at the receiving end can be expressed as

$$P = \frac{V_s V_r}{X_L} \sin(\delta_s - \delta_r) = \frac{V^2}{X_L} \sin \delta \quad (1)$$

and

$$Q = \frac{V_s V_r}{X_L} (1 - \cos(\delta_s - \delta_r)) = \frac{V^2}{X_L} (1 - \cos \delta) \quad (2)$$

The SSSC introduces a virtual compensating reactance, X_q (both inductive and capacitive), in series with the transmission line inductive reactance X_L . Now the expressions for the real and reactive powers are,

$$P = \frac{V^2}{X_{eff}} \sin \delta = \frac{V^2}{X_L (1 - \frac{X_q}{X_L})} \sin \delta \quad (3)$$

and

$$Q = \frac{V^2}{X_{eff}} (1 - \cos \delta) = \frac{V^2}{X_L (1 - \frac{X_q}{X_L})} (1 - \cos \delta) \quad (4)$$

where, X_{eff} is the effective reactance of the transmission line, including the emulated variable reactance inserted through the injected voltage source supplied by the SSSC. X_q is negative when the SSSC is operated in the inductive mode and positive when the SSSC is operated in the capacitive mode.

With 48 - pulse VSI, AC filters are not required. The inverter described is harmonic neutralized. The instantaneous values of the phase-to-phase voltage and the phase to neutral voltage of the 48 pulse inverter output voltage are expressed as Eq. (5) and (6)

$$V_{ab48}(t) = 8 \sum V_{ab48} \sin(m\omega t + 18.75^\circ m + 11.25^\circ t) \quad (5)$$

$$V_{an48}(t) = \frac{8}{\sqrt{3}} \sum_{m=1}^{\infty} V_{an48} \sin(m\omega t + 18.75^\circ m - 11.25^\circ t) \quad (6)$$

Where,

$$V_{ab48} = \frac{4}{m\pi} V_{DC} \cos \frac{\pi}{6} m \quad (7)$$

$$V_{an48} = \frac{4}{3m\pi} V_{DC} (1 + \cos \frac{\pi}{3} m) \quad (8)$$

and

$$m = 48r \pm i, r=0, 1, 2, \dots$$

$i=1$, for positive sequence harmonics and $i=-1$, for negative sequence harmonics

The voltages V_{bc48} and V_{ca48} exhibit a similar pattern except phase shifted by 120° and 240° respectively. Similarly, the phase voltages V_{bn48} and V_{cn48} are also phase shifted by 120° and 240° respectively.

III. DECOUPLED CONTROL SCHEME FOR SSSC

The main function of the SSSC is to dynamically control the power flow over the transmission line. The control scheme proposed earlier [3] is based on the line impedance control mode in which the SSSC compensating voltage is derived by multiplying the current amplitude with the desired compensating reactance X_{qref} . Since it is difficult to predict X_{qref} under varying network contingencies, in the proposed scheme, the controller is modified as shown in fig. 2 to operate the SSSC in the automatic power flow control mode [4]. In this mode, the reference inputs to the controller are P_{ref} and Q_{ref} , which are to be maintained in the transmission line despite system changes. The instantaneous power is obtained in terms of d-q quantities as,

$$P_{ref} = \frac{3V_d I_d}{2} \text{ and } Q_{ref} = \frac{3V_q I_q}{2} \quad (9)$$

From equation (9), the required current references are calculated as follows:

$$I_{dref} = \frac{2P_{ref}}{3V_d} \text{ and } I_{qref} = \frac{2Q_{ref}}{3V_d}$$

The line current I_{abc} and the line voltage V_{abc} are sensed at the point B2 on the transmission line of Fig. 1 and are converted into d-q components. The desired current references I_{dref} and I_{qref} are compared with actual current components I_d and I_q respectively and the error signals are processed in the neural controller. Initially PI controller is designed [5]-[6]. Based on the controller parameters, the required small displacement angle β to control the angle of the injected voltage with respect to the line current has been derived. A Phase Locked Loop (PLL) is used to determine the instantaneous angle θ of the three-phase line voltage V_{abc} . The current I_{abc} is decoupled into I_d and I_q of the three phase line currents are used to determine the angle θ_{ir} relative to the voltage V_{abc} . Depending upon the instantaneous reactive power with respect to the desired value either $(\pi/2)$ is added (inductive) or subtracted (capacitive) with β . Thus, the required phase angle is

derived as $\theta_{ref} = \theta + \theta_{ir} + \beta \pm (\pi/2)$. The modulation index m derived from the active power control part of the circuit and the phase angle θ_{ref} are applied to the PWM modulator to generate the SSSC compensating voltage. Using θ_{ref} and m , the fundamental component of PWM inverter output voltage is obtained as in equation (11),

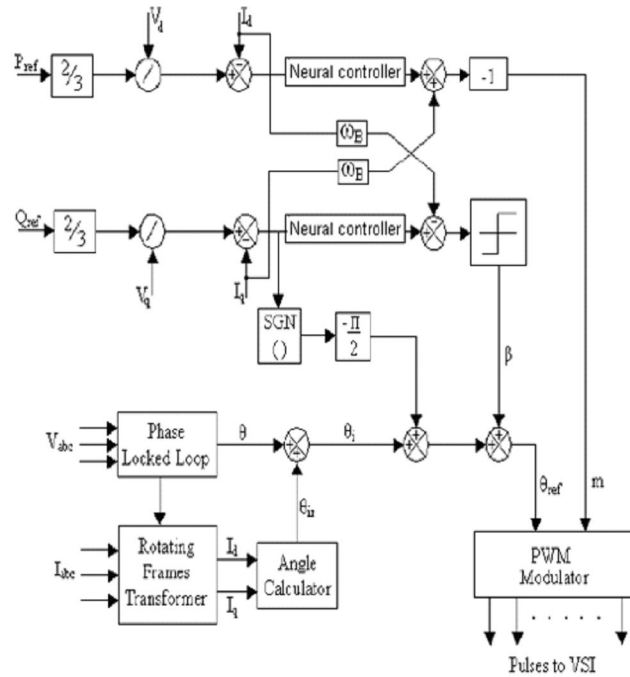
$$V_{sine} = m \sin(2\pi ft - \theta_{ref}) \quad (11)$$


Fig. 2. SSSC closed loop control scheme.

IV. CHOPPER CONTROL FOR SMES

An electronic interface known as chopper is needed between the energy source and the VSI. For VSI the energy source compensates the capacitor charge through the electronic interface and maintains the required capacitor voltage. Two-quadrant n-phase DC-DC converter as shown in Fig. 3 is adopted as interface. Here 'n' is related to the maximum current driven by the superconducting device. The DC-DC chopper solves the problems of the high power rating requirements imposed by the superconducting coil to the SSSC.

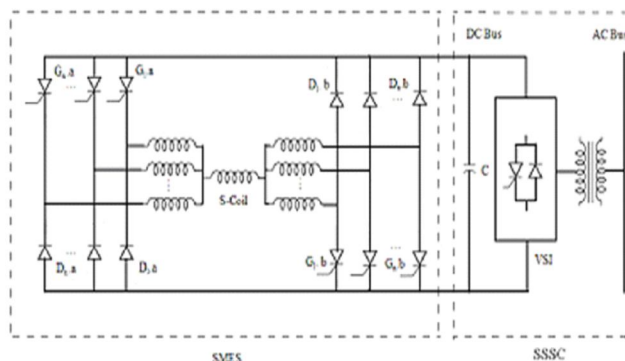


Fig. 3. Circuit diagram of chopper

For generating the gating pulses for VSI and the DC-DC chopper, internal control block is designed. Fig. 4 shows the block diagram for the estimation of duty cycle for proposed system [14]. The control scheme includes the decoupled control for the real and reactive power. The two independent reference signals are the reactive current and the active current. From these reference signals the amplitude and phase ratings of the voltage at the VSI is determined. The duty cycle D is estimated from the active power ratings that the SSSC should inject from the voltage at the DC bus and from the current stored into the SMES coil. This estimated value of D_{est} is adjusted through a closed loop control whose function is eliminating the voltage error between the calculated and the real voltage ratings at the DC bus.

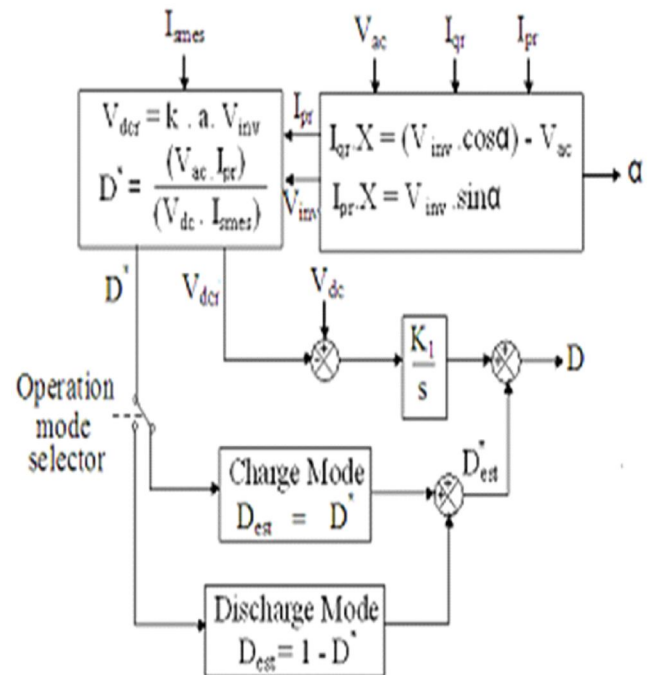


Fig. 4. Block diagram for the estimation of duty cycle

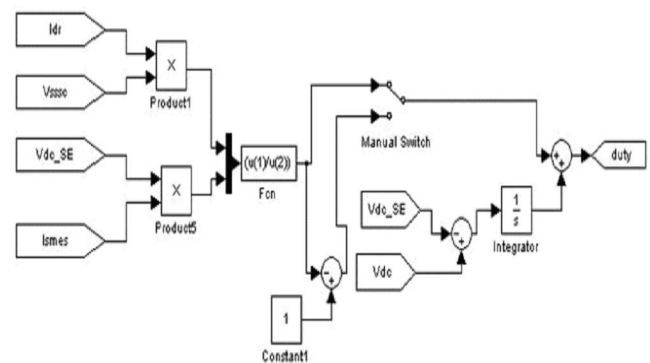


Fig. 5. Simulink diagram for the estimation of duty cycle

V. SIMULATON RESULTS AND DISCUSSIONS

The analysis is carried out for two cases (a) and (b). Case (a) is discussed for the PI control for 48-pulse inverter based SSSC without SMES and case (b) is discussed for the PI control for 48-pulse inverter based SSSC with SMES and are simulated using MATLAB/Simulink. The specifications of the proposed test system are listed in Table I.

A three phase fault is simulated in line2 near the SSSC and generator in area1 at 0.2sec and the fault is cleared at 0.7 sec and the results are analysed. The power output from the generator in area1 for case (a) and (b) are shown in figures 6 and 7 respectively. From the figures it is clear that the oscillations are more and the peak value is higher for the case (a) compared to case (b). The waveforms of the terminal voltage of the generator in area 1 are shown in figures 8 and 9 for cases (a) and (b) respectively.

Figures 10 and 11 show the real power flow in line 2 for cases (a) and (b) respectively. The steady power flow occurs for case (b) compared to case (a). Figure 12 shows the injected voltage in the transmission line. It is clear from the figure the voltage is injected during the fault period from SSSC.

TABLE I
Specifications of Test System

Parameters	Values
Rated voltage	500 kV
MVA SSSC	100 MVA
Base voltage	500 kV
Resistance	0.1 p.u
Reactance	0.3 p.u
Transmission line X_L	0.25 p.u
Transmission line R_L	0.05 p.u
D.C voltage	20 kV
Rated power	70 MVAR
D.C capacitance	2000 μ F
Series transformer rated voltage	20 kV/ 500 kV
SMES (Inductance)	2 H

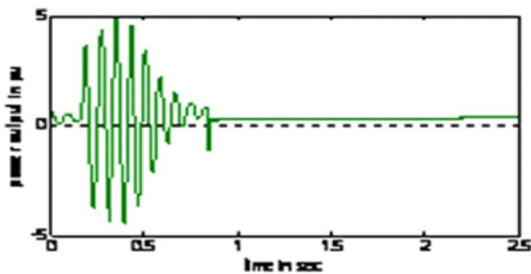


Fig.6. Power output from generator in area 1 for case (a)

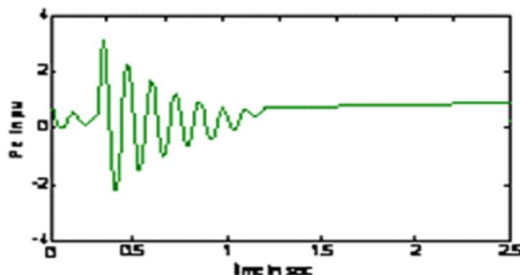


Fig.7. Power output from generator in area 1 for case (b)

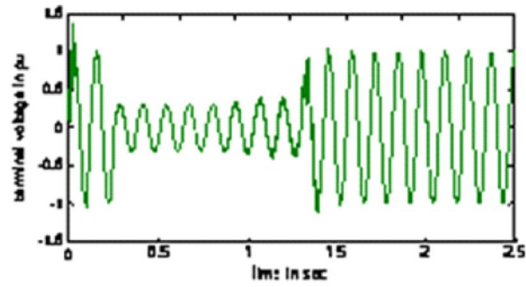


Figure 8. Terminal voltage of generator in area 1 for case (a)

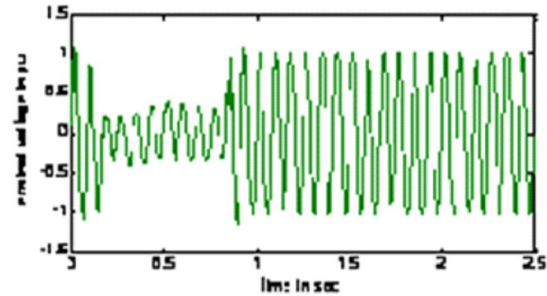


Figure 9. Terminal voltage of generator in area 1 for case (b)

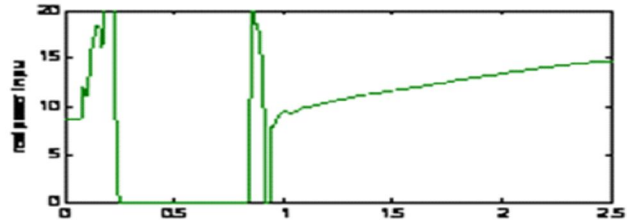


Figure 10. Real power flow in line 2 for case (a)

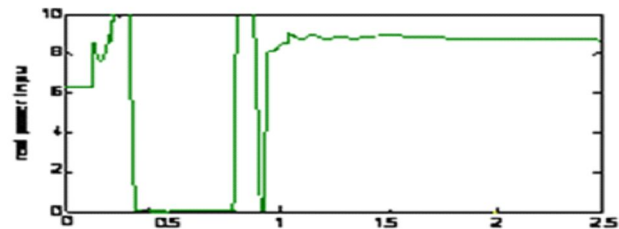


Figure 11. Real power flow in line 2 for case (b)

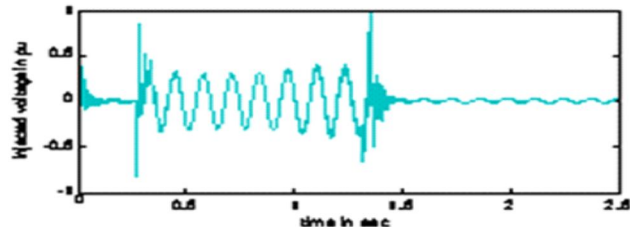


Fig. 12. Injected voltage from SSSC

VI. CONCLUSIONS

The dynamic performances of PI control based SSSC with and without SMES for the test system are analyzed with Matlab/Simulink. The SSSC is realized with 48 – pulse inverter generating symmetrical output voltages of desired magnitude and phase angle with very low harmonic

components. In this paper SMES with two quadrant chopper control play an important role in real power exchange. A PI control based SSSC with and without SMES has been developed to improve transient stability performance of the power system. It is inferred from the results that the SSSC with SMES is very efficient in transient stability enhancement and effective in damping the power oscillations and to maintain power flow through transmission lines after the disturbances.

ACKNOWLEDGMENT

We sincerely thank the Management, Secretary and Principal of Sona College of Technology, Salem for their complete support in doing this research work.

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